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Jerry J.	Battista	Canada

☒ Additional inventors are being named on the 1 separately numbered sheets attached hereto

TITLE OF THE INVENTION (500 characters max)

FAST INVERSE DOSE OPTIMIZATION

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ENCLOSED APPLICATION PARTS *(check all that apply)*

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Respectfully submitted,
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TELEPHONE 416-364-7311 Docket Number: 8611-35

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PROVISIONAL APPLICATION COVER SHEET

Additional Page

Docket Number 9611-35

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FEE CALCULATION

1. BASIC FILING FEE

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1001	770	2001	385	Utility filing fee	
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Independent Claims		- 3** =		x		=	0.00
Multiple Dependent							

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1202	18	2202	9	Claims in excess of 20
1201	86	2201	43	Independent claims in excess of 3
1203	290	2203	145	Multiple dependent claim, if not paid
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1205	18	2205	9	** Reissue claims in excess of 20 and over original patent

SUBTOTAL (2) ($) 0.00

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1053	130	1053	130	Non-English specification	
1812	2,520	1812	2,520	For filing a request for *ex parte* reexamination	
1804	920*	1804	920*	Requesting publication of SIR prior to Examiner action	
1805	1,840*	1805	1,840*	Requesting publication of SIR after Examiner action	
1251	110	2251	55	Extension for reply within first month	
1252	420	2252	210	Extension for reply within second month	
1253	950	2253	475	Extension for reply within third month	
1254	1,480	2254	740	Extension for reply within fourth month	
1255	2,010	2255	1,005	Extension for reply within fifth month	
1401	330	2401	165	Notice of Appeal	
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1501	1,330	2501	665	Utility issue fee (or reissue)	
1502	480	2502	240	Design issue fee	
1503	640	2503	320	Plant issue fee	
1460	130	1460	130	Petitions to the Commissioner	
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1806	180	1806	180	Submission of Information Disclosure Stmt	
8021	40	8021	40	Recording each patent assignment per property (times number of properties)	
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Patent Application Data Sheet

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BERESKIN & PARR

UNITED STATES PROVISIONAL APPLICATION

Title: Fast Inverse Dose Optimization

Inventors: Samuel Pedro Goldman, Jerry J. Battista and Jeff Z. Chen

FIDO - Fast Inverse Dose Optimization

Detailed Description of Invention

The most fundamental requirements of a radiation treatment optimization are: (*i*) dose is homogeneously deposited in the Planning Target Volume (PTV); (*ii*) the dose deposited in any Organ At Risk (OAR) does not exceed a threshold value and ideally should be zero; (*iii*) the dose deposited in All The Rest (ATR), *i.e.* organs and tissue not included in the PTV and OARs, should be as small as possible and ideally zero to minimize the risk of secondary carcinogenesis; (*iv*) the dose gradient crossing the PTV boundaries should be as high as possible. Optimizations are pursued by the minimization of a positive-definite objective function. A successful optimization will yield a global minimum to this objective function in a short computation time with physically achievable beamlet intensities.

This work presents a new approach to radiation treatment optimization that is very fast and yields a global minimum of the objective function without the use of a search routine but rather solves a linear system of equations. The possibility of such a direct optimization scheme has been known for decades but it has been impossible to implement rigorously using conventional quadratic objective functions because optimized results are only achievable with unphysical negative beamlet intensities [3]. Once an ad-hoc condition requiring the beamlet intensities to be positive is introduced (i.e. force negative values to be zero), the linear method yields a dose distribution with artefacts. Alternatively, one may pursue a minimum of the objective function by a direct search over all possible positive beam intensities, but this is a very time-consuming approach. In our work the negative-intensities problem is dealt with *within the objective function* and not as an externally imposed ad-hoc requirement.

We summarize now our approach. In the following we call "organ" any organ, target volume, region of tissue, identifiable anatomical entity or any defined volume within the volume exposed to radiation. For simplicity we will divide the set of organs indo organs that must receive a certain dose and organs that should receive no dose or a dose as small as possible. A typical objective function O satisfying the optimization conditions stated above is of the form:

$$O = \sum_{h}^{\text{all organs with required dose}} p_h^{dose} O_h^{dose} + \sum_{m}^{\text{all organs without required dose}} p_m^{no\text{-}dose} O_m^{no\text{-}dose}$$

where the p_h are importance coefficients and the objectivity terms are:

$$O_h^{dose} = \sum_{x \in organ_h} \left(\sum_{i}^{\text{all beamlets}} w_i d_i(x) - d^{organ_h} \right)^2$$

$$O_m^{no\text{-}dose} = \sum_{x \in organ_m} \left(\sum_{i}^{\text{all beamlets}} w_i d_i(x) \right)^2$$

where w_i is the weight of beamlet i, d_i is the dose deposited at destination point x by beamlet i and d^{organ_h} is the dose required in organ h.

The main reason for the traditional appearance of negative weights upon optimization of the obejctive function O is the fact that we require satisfying two conflicting demands: on one hand we require $O^{ATR} = 0$ and on the other we require radiation to pass through the ATR (and possibly OARs) to reach the PTV. A correct requirement on O_{ATR} (and OARs) is that $O^{no\text{-}dose}$ should be minimized and $O^{no\text{-}dose}$ *should be zero only if the weights of all the beamlets passing through the "no-dose" organs are zero.* This requirement is satisfied if instead of that standard $O^{no\text{-}dose}$ above, we use new terms of the form

Detailed Description of Invention

$$\bar{O}_n^{no-dose} = \sum_{x \in organ_n} \sum_i^{all\ beamlets} w_i^2 d_i^2(x)$$ °°°°*novel idea*°°°°

We have as well added another term to the objective function that replaces the unrealistic zero-limit for the beamlet weights with an equal-weight limit (cylindrical symmetry) which is usually the initial set of weights before optimization. This term is of the form

$$O^{sym} = \sum_i^{all\ beamlets} \left(w_i^2 - w_i \right).$$ °°°°*novel idea*°°°°

With the weights normalized to

$$\sum_i^{all\ beamlets} w_i = \text{total number of beamlets},$$

O^{sym} is positive and its minimum is zero when $w_i = 1$ for all i. O^{sym} provides the most powerful constraint to avoid negative weights.

With the new terms introduced above, the new objective function to be used is of the form:

$$O = \sum_h^{all\ organs\ with\ required\ dose} p_h^{dose} O_h^{dose} + \sum_n^{all\ organs\ without\ required\ dose} \bar{p}_n^{no-dose} \bar{O}_n^{no-dose} + p_{sym} O^{sym}$$ °°°°*novel idea*°°°°

Although not necessary (and in general counterproductive) the terms $O_m^{no-dose}$ can also be added to the objective function. In our calculations, the terms $O_m^{no-dose}$ were given non-zero importance coefficients when we wanted to demonstrate the appearance of negative weights upon optimization. With this consideration a more general objective function is:

$$O = \sum_h^{all\ organs\ with\ required\ dose} p_h^{dose} O_h^{dose} + \sum_n^{all\ organs\ without\ required\ dose} \bar{p}_n^{no-dose} \bar{O}_n^{no-dose} + p_{sym} O^{sym} + \sum_m^{all\ organs\ without\ required\ dose} p_m^{no-dose} O_m^{no-dose}.$$

°°°°*novel idea*°°°°

Where the coefficients p_s are the importance parameters for organ s within an objectivity component and p_{sym} is the importance parameter of the asymptotic symmetry condition. The optimization problem for all the beam intensities is reduced to the solution of a linear system of equations as is shown in the following paragraphs.

The optimum of the objective function is obtained by minimizing the objective function from the system of equations:

The optimum of the positive-definite objective function O is obtained by minimizing O with respect to all the weights w_i. We perform this minimization by requiring the set of first derivatives of O to satisfy:

$$0 = \frac{\partial O}{\partial w_j} \quad \text{for all } w_j.$$

Consider the term O_h^{dose}:

$$\frac{\partial O_h^{dose}}{\partial w_j} = 2 \sum_{x \in organ_h} d_j(x) \left(\sum_i^{all\ beamlets} w_i d_i(x) - d^{prescr_h} \right)$$

Detailed Description of Invention

In our novel approach, ***we exchange the order of the summations*** to obtain:

$$\frac{\partial O_k^{dose}}{\partial w_j} = 2\sum_i^{\text{all beamlets}} w_i \left(\sum_{x \in organ_k} d_i(x) d_j(x) \right) - 2d^{organ_k} \sum_{x \in organ_k} d_j(x)$$ °°°°***novel idea***°°°°

This simple exchange in the summation order simplifies enormously the problem! We are now able to formulate the problem only in terms of the beamlet weights. The x-dependence (destination point dependence) has been eliminated by summing over all destination points *in advance*. We can define now the x-independent arrays:

$$\alpha_{ij}^{organ_k} = \sum_{x \in organ_k} d_i(x) d_j(x)$$ °°°°***novel idea***°°°°

and

$$\beta_j^{organ_k} = d^{organ_k} \sum_{x \in organ_k} d_j(x)$$ °°°°***novel idea***°°°°

The optimization problem for the optimal weights w_i is given by the solution to the system of linear algebraic equations:

$$\sum_j^{\text{all beamlets}} \alpha_{ij} w_j = \beta_i$$ °°°°***novel idea***°°°°

where

$$\alpha_{ij} = \sum_k^{\substack{\text{all organs with}\\ \text{required dose}}} p_k^{dose} \alpha_{ij}^{organ_k} + \sum_m^{\substack{\text{all organs}\\ \text{without}\\ \text{required dose}}} p_m^{no-dose} \alpha_{ij}^{organ_m} + \sum_n^{\substack{\text{all organs}\\ \text{without}\\ \text{required dose}}} \bar{p}_n^{no-dose} \alpha_{ij}^{organ_n} \delta_{ij} + p_{sym} \delta_{ij}$$ °°°°***novel idea***°°°°

and

$$\beta_i = \sum_k^{\substack{\text{all organs with}\\ \text{required dose}}} p_k^{dose} \beta_i^{organ_k} + \frac{1}{2} p_{sym}$$ °°°°***novel idea***°°°°

The solution to the optimization problem is obtained by the numerical inversion of the matrix α_{ij}:

$$w_i = \sum_j^{\text{all beamlets}} \alpha_{ij}^{-1} \beta_j$$ °°°°***novel idea***°°°°

Fast Inverse Dose Optimization (FIDO) for IMRT via Matrix Inversion with no Negative Intensities

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Abstract

A fast optimization algorithm is very important for inverse planning of Intensity Modulated Radiation Therapy (IMRT), and for adaptive radiotherapy of the future. Conventional numerical search algorithms such as the conjugate gradient search, conducted with positive beam weight constraints, generally require many iterations and may produce suboptimal results due to trapping in local minima. A direct solution of the inverse problem using conventional quadratic objective functions without positive beam constraints is more efficient but will result in unrealistic negative beam weights. We present here a direct solution of the inverse problem which does not result in unacceptable negative beam weights. The objective function for the optimization of beam intensities for large number of beamlets is reformulated such that the optimization problem is reduced to a linear set of equations. The optimal set of intensities is found through a matrix inversion, and negative beamlet intensities are avoided without the need for externally imposed constraints. The method has been applied to a test phantom and to a few clinical cases. We were able to achieve highly conformal dose distributions with very short optimization times. Typical optimization times for a single anatomical slice using a single processor desktop computer are: 0.2 sec. for 400 beamlets; 8 sec. for 1,000 beamlets; 40 sec. for 2,000 beamlets and 2.5 min for 3,000 beamlets. These times can be substantially further improved using a better optimization routine for matrix inversion. In conclusion, the new method provides a fast and robust technique to find a global minimum that yields excellent results for the inverse planning of IMRT.

Keywords

Inverse planning, optimization, objective function.

Introduction

Intensity Modulated Radiation Therapy (IMRT) is becoming a new standard for radiotherapy. Given the better conformal dose distributions obtained through IMRT and its dynamic delivery features, adaptive radiotherapy becomes an important factor to be considered. A fast optimization algorithm is crucial not only for designing good radiation treatment plans but also for the successful implementation of future interactive adaptive treatment techniques. Conventional optimization algorithms using numerical searches such as the conjugate gradient search [1-2] with positive beam weight constraints usually require many iterations (i.e. long computation times) and may result in suboptimal plans due to trapping in local minima of the objective function. A direct solution of the inverse problem using conventional quadratic objective functions without imposing positive beam constraints will be computationally faster but will result in unrealistic negative beam weights. We present here a very fast method for the direct solution of the inverse problem (FIDO) that avoids the difficulty of negative beam weights and preserves efficiency.

Method

The most fundamental requirements of a radiation treatment ptimization are: (*i*) dose is homogeneously deposited in the Planning Target Volume (PTV); (*ii*) the dose deposited in any Organ At Risk (OAR) does not exceed a threshold value and ideally should be zero; (*iii*) the dose deposited in All The Rest (ATR), *i.e.* organs and tissue not included in the PTV and OARs, should be as small as possible and ideally zero to minimize the risk of secondary carcinogenesis; (*iv*) the dose gradient crossing the PTV boundaries should be as *high* as possible. Optimizations are pursued by the minimization of a positive-definite objective function. A successful optimization will yield a global minimum to this objective function in a short computation time with physically achievable beamlet intensities.

This work presents a new approach to radiation treatment optimization that is very fast and yields a global minimum of the objective function without the use of a search routine but rather solves a linear system of equations. The possibility of such a direct optimization scheme has been known for decades but it has been impossible to implement rigorously using conventional quadratic objective functions because optimized results are only achievable with unphysical negative beamlet intensities [3]. Once an ad-hoc condition requiring the beamlet intensities to be positive is introduced (i.e. force negative values to be zero), the linear method yields a dose distribution with artefacts. Alternatively, one may pursue a minimum of the objective function by a direct search over all possible positive beam intensities, but this is a very time-consuming approach. In our work the negative-intensities problem is dealt with *within the objective function* and not as an externally imposed ad-hoc requirement.

We summarize now our approach. For simplicity we will consider a single PTV, a single OAR and a single ATR. A typical objective function O satisfying the optimization conditions stated above is f the form:

$$O = p_{PTV}O_{PTV} + p_{OAR}O_{OAR} + p_{ATR}O_{ATR}$$

where the p_k are importance coefficients and the objectivity terms are:

$$O_{PTV} = \sum_{x\in PTV}\left(\sum_i^{\text{all beamlets}} w_i d_i(x) - d^{PTV}\right)^2,$$

$$O_{OAR} = \sum_{x\in OAR}\left(\sum_i^{\text{all beamlets}} w_i d_i(x)\right)^2,$$

and $$O_{ATR} = \sum_{x\in ATR}\left(\sum_i^{\text{all beamlets}} w_i d_i(x)\right)^2,$$

where w_i is the weight of beamlet i, d_i is the dose deposited at destination point x by beamlet i and d^{PTV} is the dose prescribed to the PTV. The main reason for the traditional appearance of negative weights upon optimization of the objective function O is the fact that we require satisfying two conflicting demands: on one hand we require $O_{ATR} = 0$ and on the other we require radiation to pass through the ATR (and possibly OARs) to reach the PTV. A correct requirement on O_{ATR} is that O_{ATR} should be minimized and O_{ATR} *should be zero only if the weights of all the beamlets passing through the ATR are zero*. This requirement is satisfied if instead of O_{ATR} we use a new ATR term of the form

$$\tilde{O}_{ATR} = \sum_{x\in ATR}\sum_i^{\text{all beamlets}} w_i^2 d_i^2(x).$$

Similarly for the OAR we use:

$$\tilde{O}_{OAR} = \sum_{x\in OAR}\sum_i^{\text{all beamlets}} w_i^2 d_i^2(x).$$

We have as well added another term to the objective function that replaces the unrealistic zero-limit for the beamlet weights with an equal-weight limit (cylindrical symmetry) which is usually the initial set of weights before optimization. This term is f the form

$$O_{sym} = \sum_i^{\text{all beamlets}}\left(w_i^2 - w_i\right).$$

With the weights normalized to

$$\sum_i^{\text{all beamlets}} w_i = \text{total number of beamlets},$$

O_{sym} is positive and its minimum is zero when $w_i = 1$ for all i. With these modifications, the optimization problem for all the beam intensities is reduced again to the solution of a linear system of equations of the form:

$$\sum_j \alpha_{ij} w_j = \beta_i \qquad (1)$$

where w_j is the (unknown) weight or intensity of beamlet j, β_i is a vector of coefficients that depends on the dose deposited by beam i within the PTV, and α_{ij} is a matrix that describes the product of the doses deposited by the intersecting pairs of beamlets i and j on different organs (each organ with its importance coefficient). The set of optimal beam weights is obtained from (1) by inversion:

$$w_i = \sum_j \alpha_{ij}^{-1}\beta_j$$

In other words, the solution to the (large) system of linear equations (1) is obtained quickly and accurately by inverting the array α_{ij} using standard matrix inversion routines.

Results

Below we present several sets of preliminary results obtained with this technique for a prostate case, a head and neck case, and an "interlocked rectangles" phantom on a 2D slice. Only primary KERMA has been included in the calculations reported here, but very similar results are obtained in dose distributions, when the calculated beam intensities are imported to a commercial treatment planning system (Theraplan Plus V3.8, Nucletron). The only difference is a slightly diffused dose to the OARs due to scatter spreading effects. In each case, we include calculation and optimization times for KERMA calculations as they were obtained on a single-processor desktop PC. The program was written in C# using the Microsoft .NET environment. The matrix inversion routine was obtained from *Numerical* Recipes [4] and translated from FORTRAN into C#. No effort has been devoted to maximize the speed of the matrix inversion procedure.

In all cases the number of gantry angles used is evenly distributed over a full 360 degree circle around the isocentre. Each beam is evenly divided into beamlets of the specified width resulting in the total number of beamlets quoted. The source to axis distance (SAD) is 100 cm. In each case we also present the DVH, scaled to 100% volume on the vertical axis and 100% dose on the horizontal axis, and a colour-coded dose deposition map with blue showing no dose deposition (primary KERMA only) and red the largest dose deposition.

Conclusions and future work

We have developed a fast and robust technique to find a global minimum that yields excellent results for the inverse optimization problem for the radiation treatment of tumours, using large sets of non-negative intensity-modulated beamlets.

Work is currently in progress on a full implementation FIDO in our treatment planning system that uses collapsed cone convolution method for dose calculation [5]. Work is proceeding as well on an efficient 3D implementation for on-line adaptive radiotherapy as might be possible with helical tomotherapy [6].

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Figure 1: Head and Neck Case. – 20 gantry angles

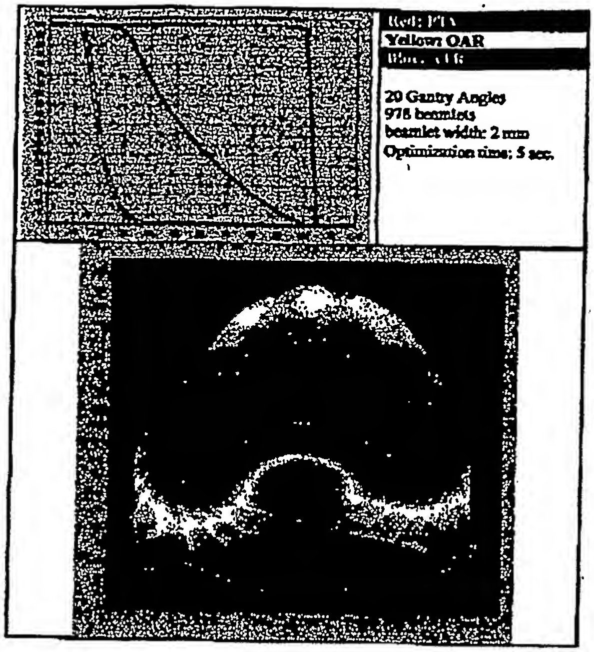


Figure 2: Head and Neck Case. – 40 gantry angles

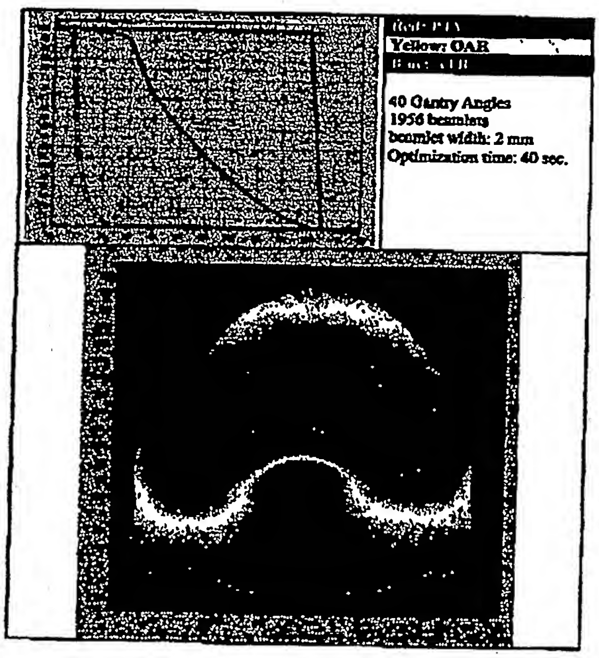
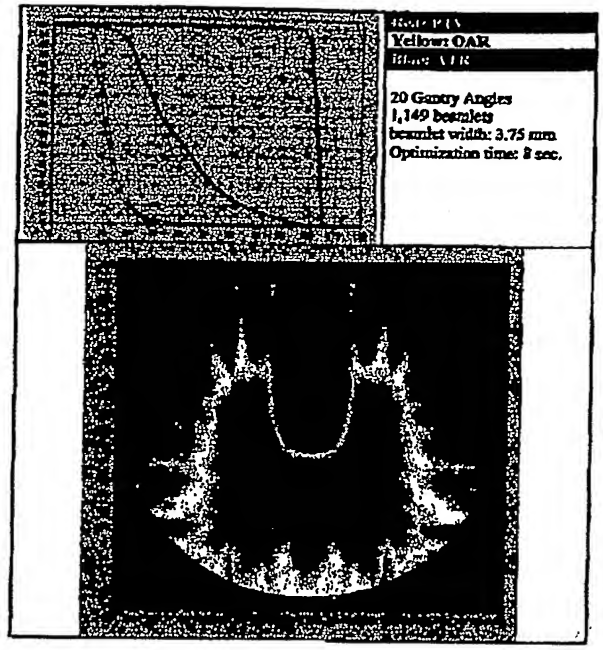
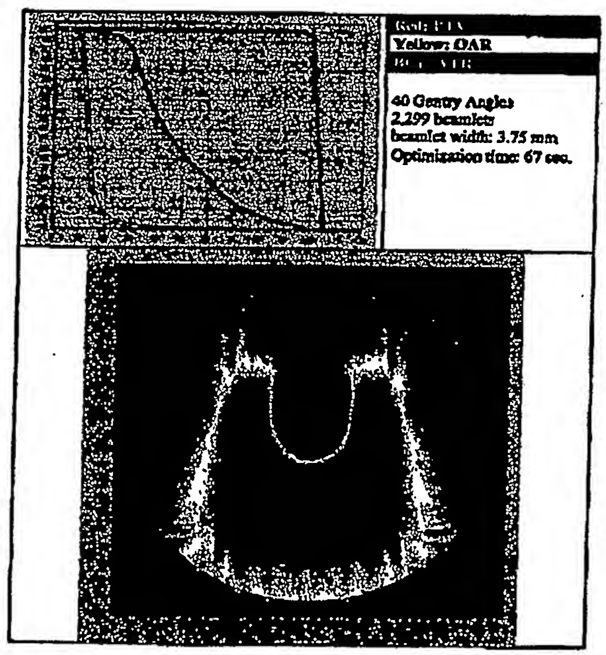


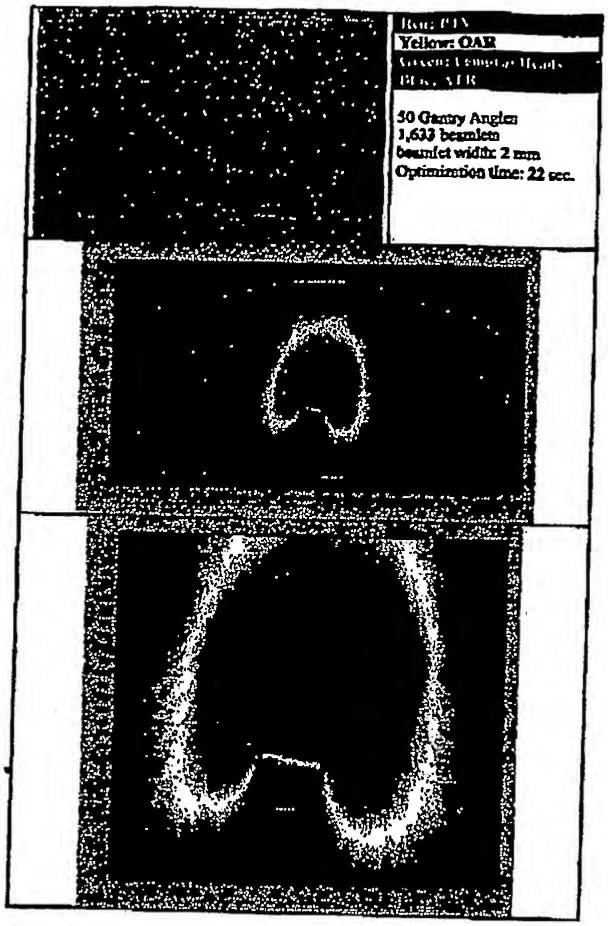
Figure 3: Interlocked Rectangles Phantom. – 20 gantry angles



Set No. 4: Interlocked Rectangles. – 40 gantry angles



Set No. 5: Prostate Case (Panoramic and close-up views).



References

[1] S. Smith and L. S. Lasdon, "Solving large sparse nonlinear programs using GRG ORSA", Journal on Computing, 4, 1-15 (1992).

[2] S. V. Spirou and C. S. Chui, "A gradient inverse planning algorithm with dose-volume constraints", Med Phys. 25(3), 321-33 (1998).

[3] S. Webb, "The physical basis of IMRT and inverse planning", Br J Radiol., 76(910), 678-89, Review (2003).

[4] Press W H, Flannery B P, Vetterling W T and Teukolsky S A, "*Numerical Recipes*" (Cambridge University Press).

[5] A. Ahnesjo, "Collapsed cone convolution of radiant energy for photon dose calculation in heterogeneous media", Med. Phys. 16, 577-592 (1989).

[6] T. R. Mackie, J. Balog, K. Ruchala, D. Shepard, S. Aldridge, E. Fitchard, P. Reckwerdt, G. Olivera, T. McNutt, M. Mehta, "Tomotherapy", Semin Radiat Oncol. 9(1), 108-117 (1999).

We claim:

1. A method for optimizing radiation treatment, said method comprising the step of resolving an objective function, said objective function comprising importance coefficients and objectivity terms.

2. A system for optimizing radiation treatment, said system comprising means for resolving an objective function.

3. A method of planning delivery of radiation therapy to maximize radiation to a planned target volume and minimize radiation to surrounding tissues outside the planned target volume, said method comprising the step of resolving an objective function.

4. The invention substantially as described and illustrated herein.